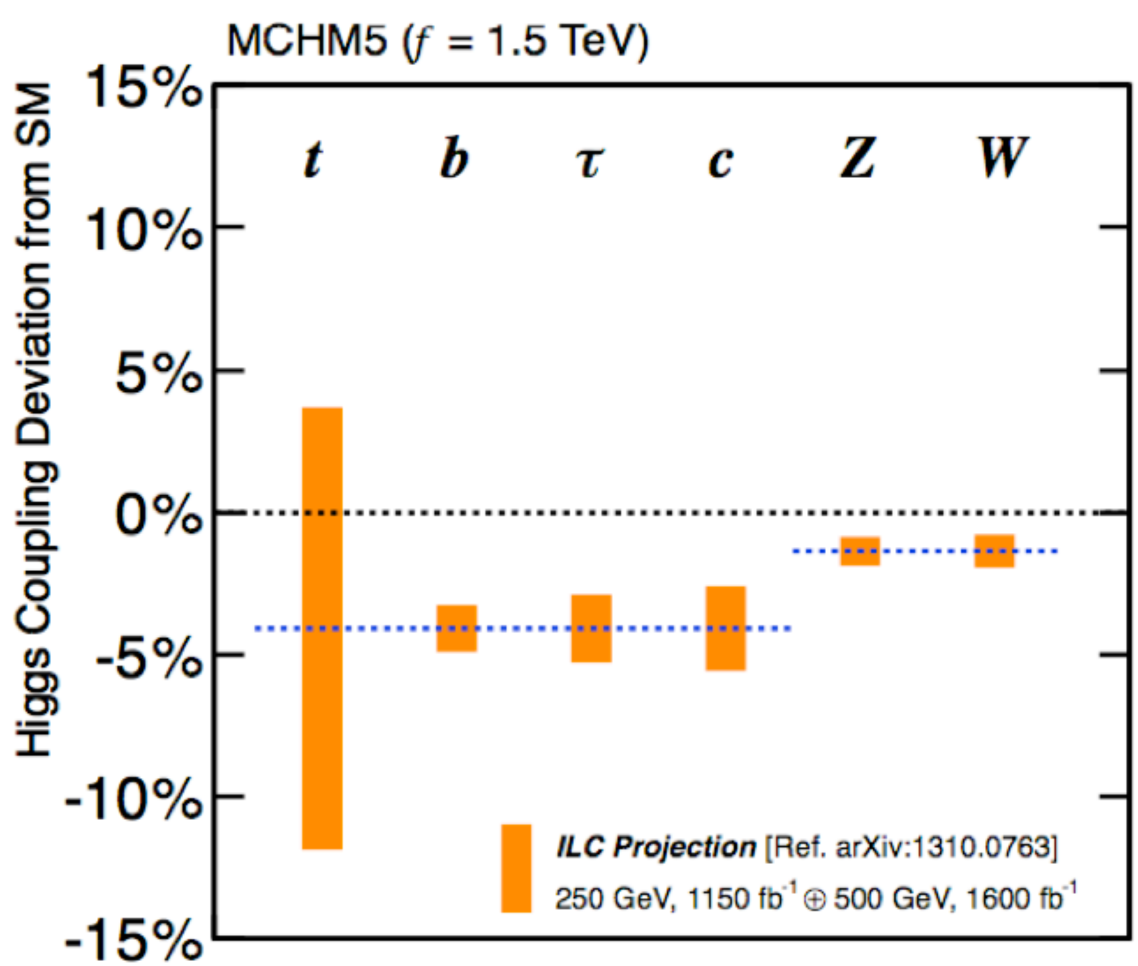
The Importance of Lattice QCD for Precision Higgs Boson Measurements



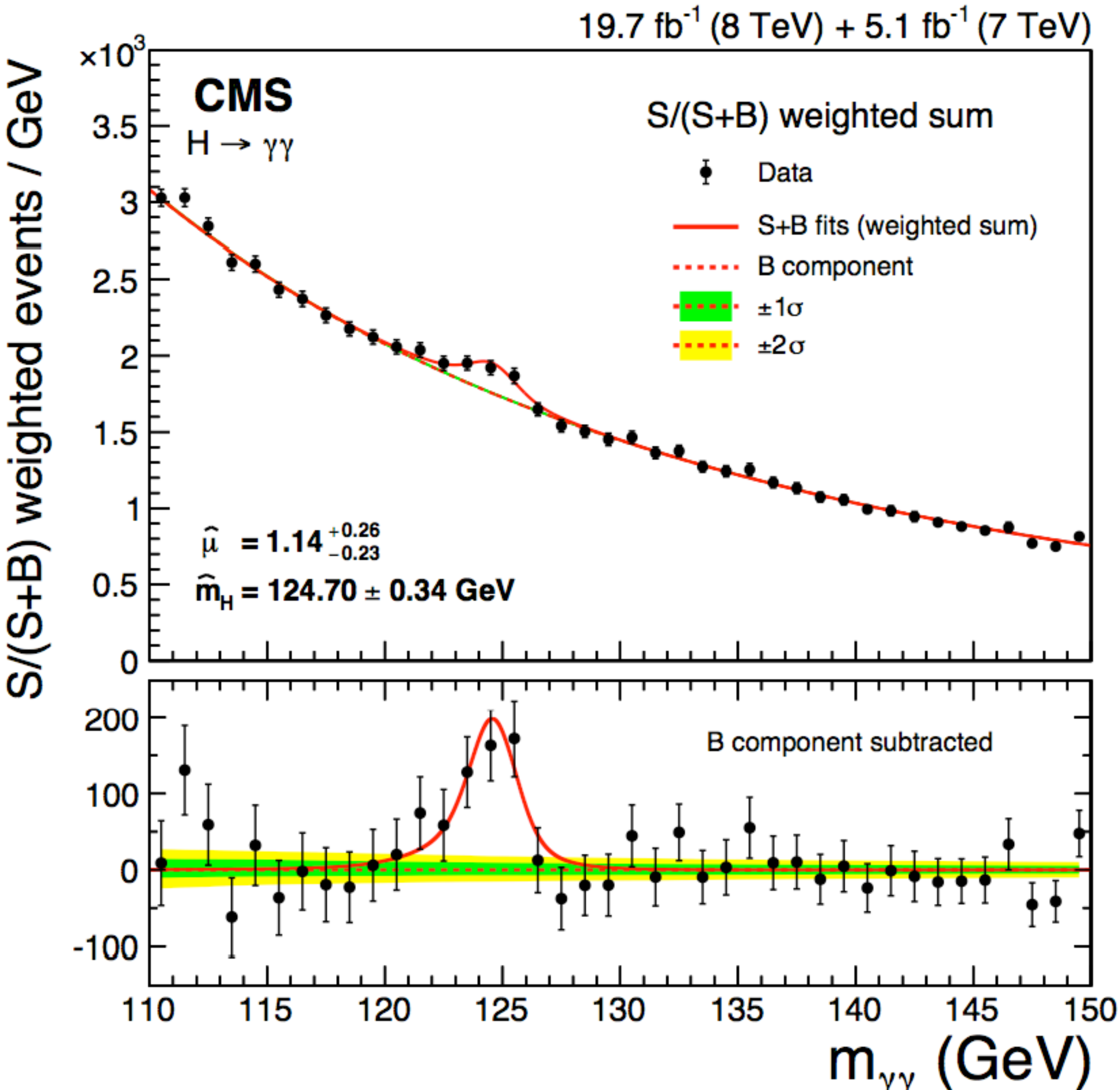
M. E. Peskin
Lattice for BSM Physics
LLNL
April 2015

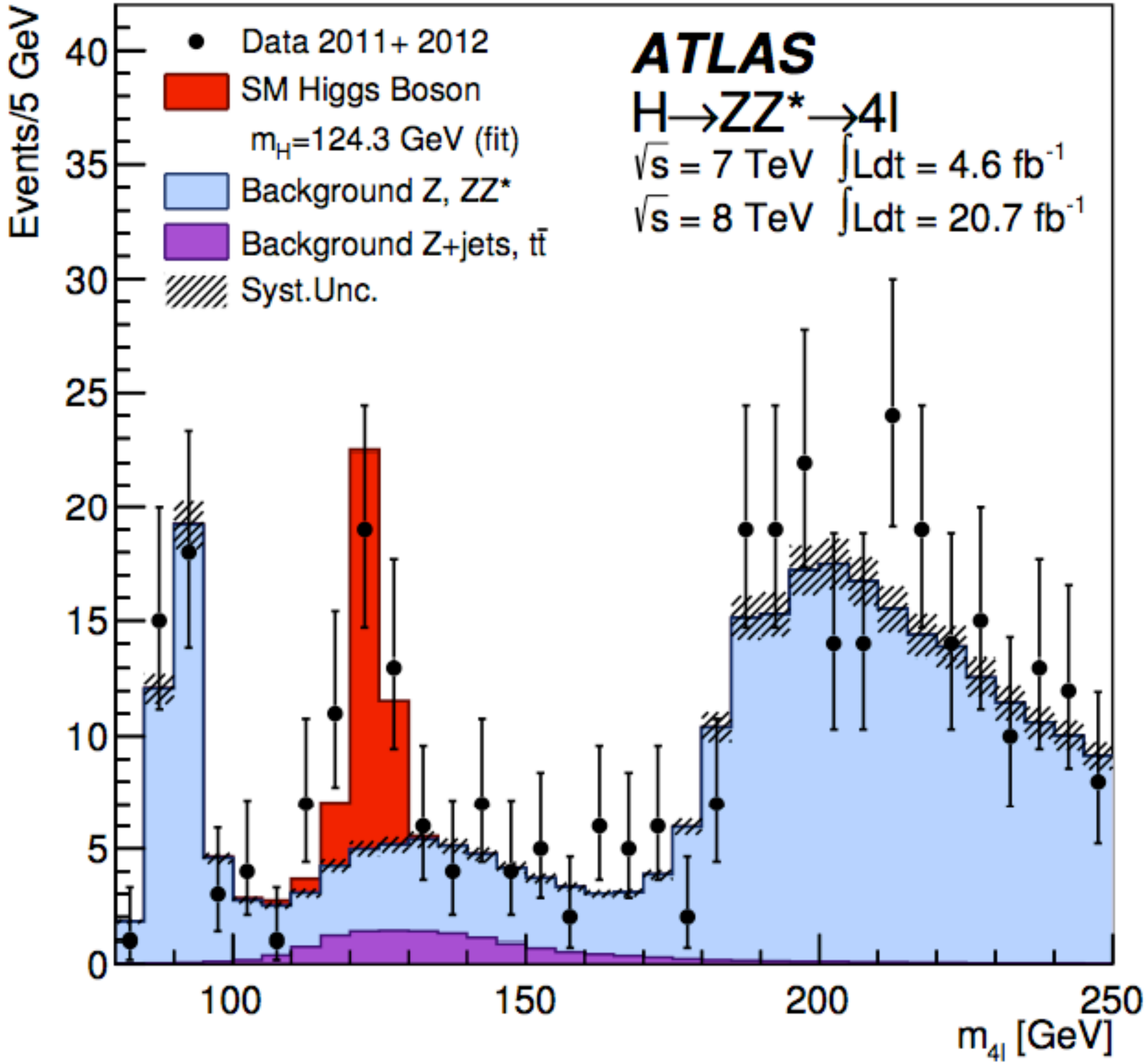
Lepage, Mackenzie, MEP, arXiv:1404.0319

Only four years ago, in the fall of 2011, it was a popular theme for discussion among particle physicists that the Higgs boson did not exist.

Searches at the LHC had eliminated most of allowed range for the Higgs boson mass. Only a small corner remained in which the Higgs could hide.

Today, the situation could not be more different.

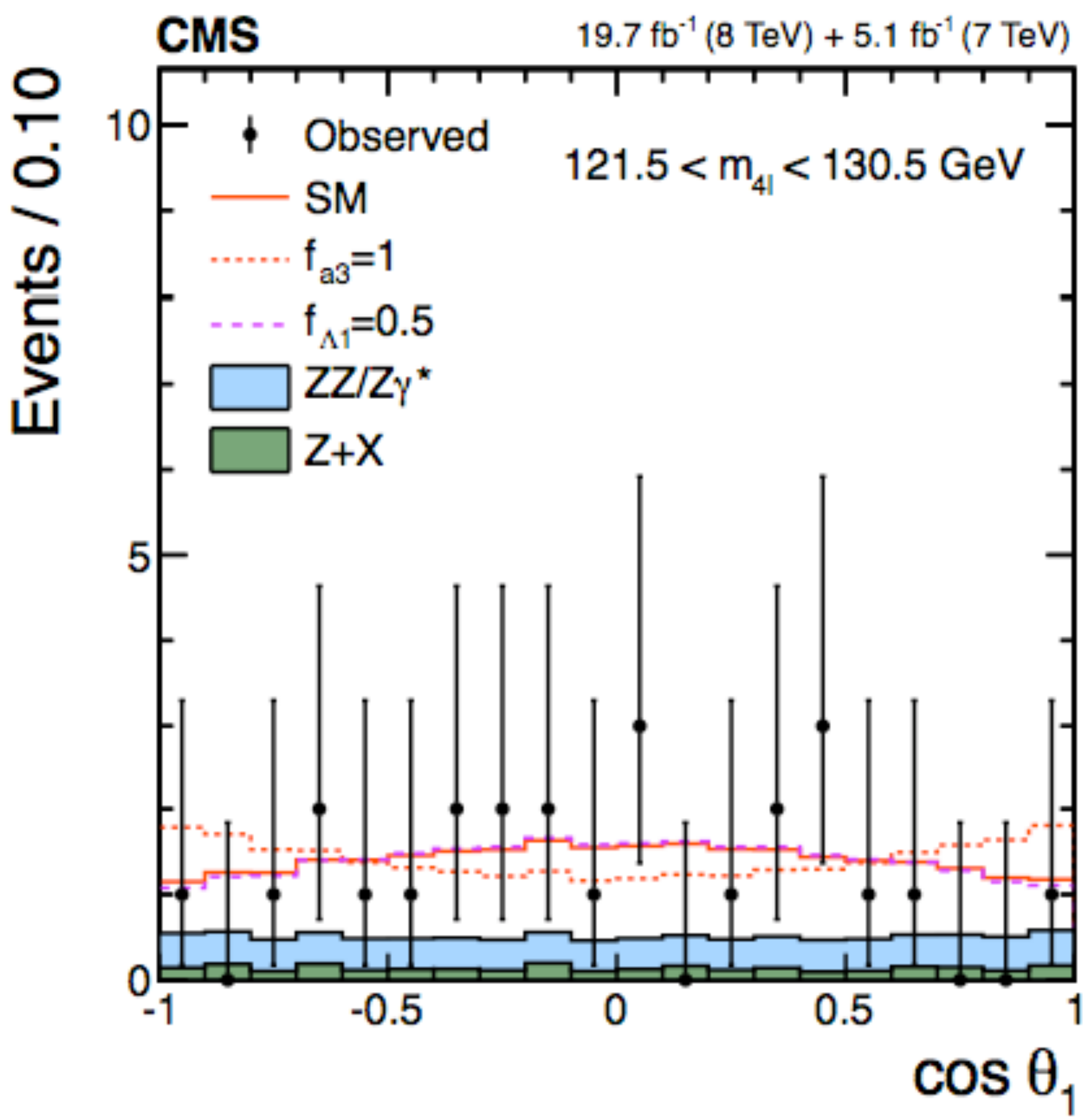

19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
$\hat{\mu} = 1.14^{+0.26}_{-0.23}$
$\hat{m}_H = 124.70 \pm 0.34$ GeV
S/(S+B) weighted events / GeV
×10^3
B component subtracted
$m_{\gamma\gamma}$ (GeV)

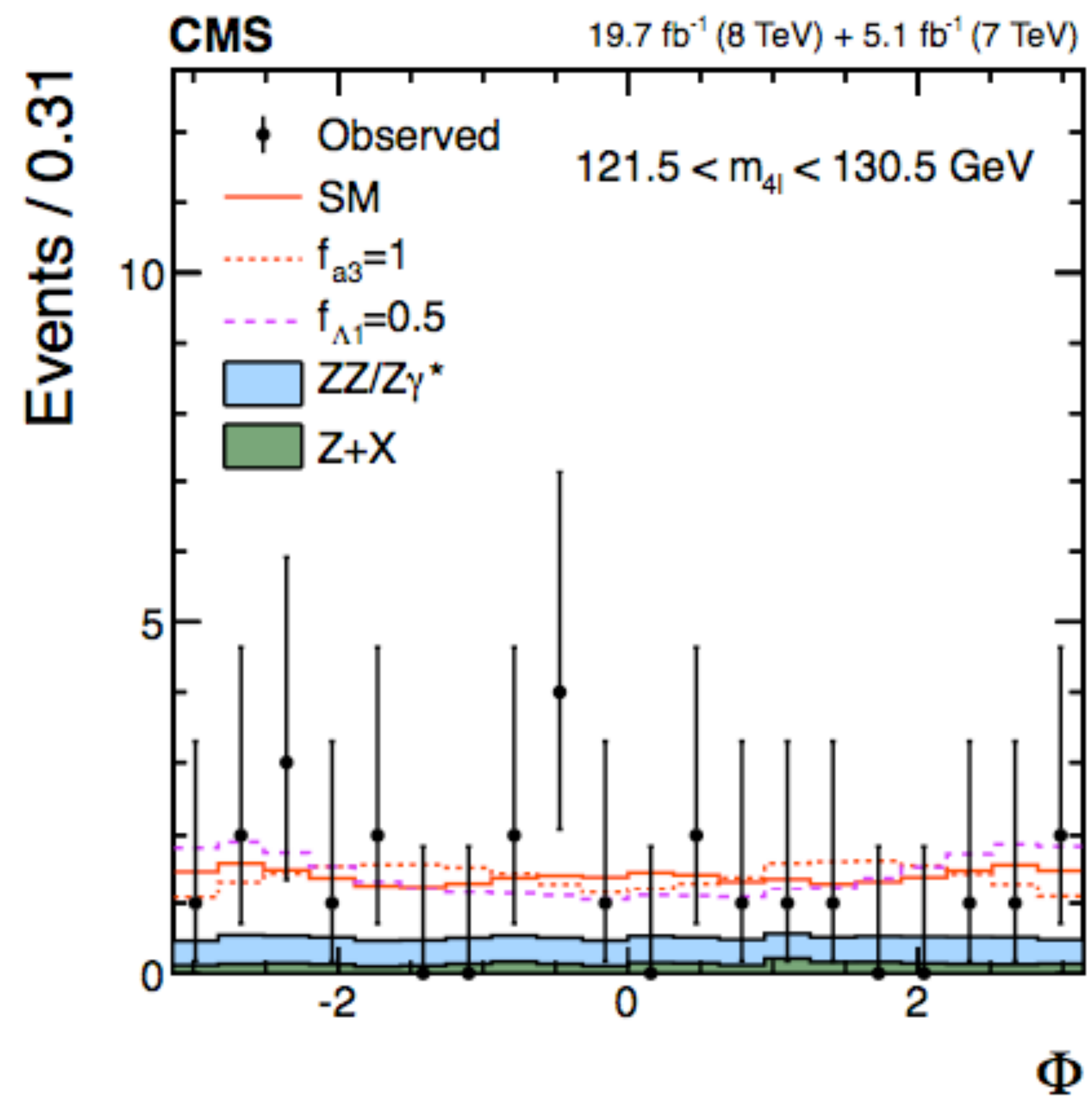


Events/5 GeV
Data 2011+ 2012
SM Higgs Boson
m_H=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, tt̄
Syst.Unc.
ATLAS
H→ZZ*→4l
√s = 7 TeV ∫Ldt = 4.6 fb-1
√s = 8 TeV ∫Ldt = 20.7 fb-1
0
5
10
15
20
25
30
35
40
100
150
200
250
m_4l [GeV]

Tests of qualitative properties predicted for the Higgs boson:

$\gamma\gamma$ decay mode	✔
ZZ decay mode	✔
WW decay mode	✔
$\tau^+\tau^-$ decay mode	✔
bb decay mode	preliminary
tt coupling	indirectly, through gg
spin-parity 0+	✔



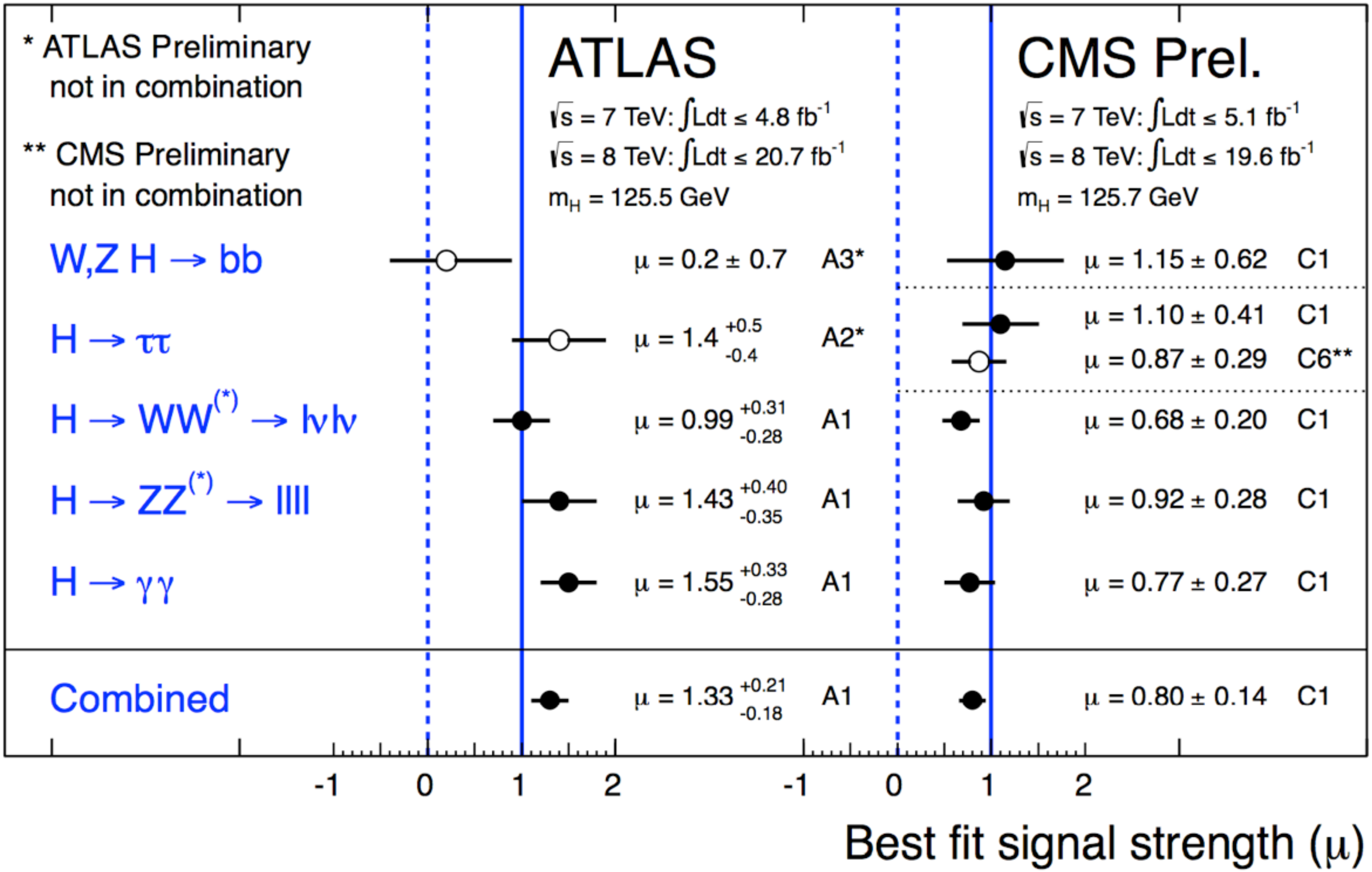


preference for Z to be longitudinally polarized

preference for Z decay planes to be parallel

The quantitative measure for used today for Higgs coupling values is the "signal strength"

$$\mu(A, B) = \frac{\sigma(A\overline{A} \to h) BR(h \to B\overline{B})}{(\text{SM expectation})}$$



PDG summary 2014

I do not think that the case is completely closed that the new particle at 125 GeV is the Higgs boson.

But, the evidence is already quite compelling, and the measurements will be qualitatively improved in the new LHC run at 13 TeV.

It is time to ask the next level of questions about the properties of the Higgs boson.

If the new particle is the Higgs boson, its properties might still not line up exactly with the predictions of the Standard Model.

There may be multiple Higgs doublets. There may be new heavy particles responsible for the form of the Higgs potential.

By making precision measurements of the Higgs boson couplings, we can use the Higgs as a tool to prove the existence of these states.

It would seem that is should not be difficult to determine whether the Higgs sector contains one field or many, elementary or composite.

However, there is a barrier:

the "Decoupling Theorem" of Howard Haber

If the Higgs sector contains one light boson of mass

$$m_h = 125 \text{ GeV}$$

and many heavy particles with minimum mass M,

the light boson has properties that agree with the SM predictions up to corrections of order

$$m_h^2 \,/\, M^2$$

Proof:

Integrate out the heavy fields. The result is the SM, plus a set of operators of minimum dimension 6.

Implication:

In most models of an extended Higgs sector or other new particles, the corrections to the Higgs couplings are at the few-% level. Precision measurement is needed to see these corrections.

However:

The pattern of corrections is different in different schemes for new physics models. There is much to learn if we can see this pattern.

Given the mass of the Higgs boson, the Standard Model makes a precise set of predictions for the couplings. These should be considered as reference values for precision measurements.

For a Higgs boson of mass 125 GeV, the prediction for the total width is $\Gamma_h = 4.1\ \mathrm{MeV}$

The branching fractions are predicted to be

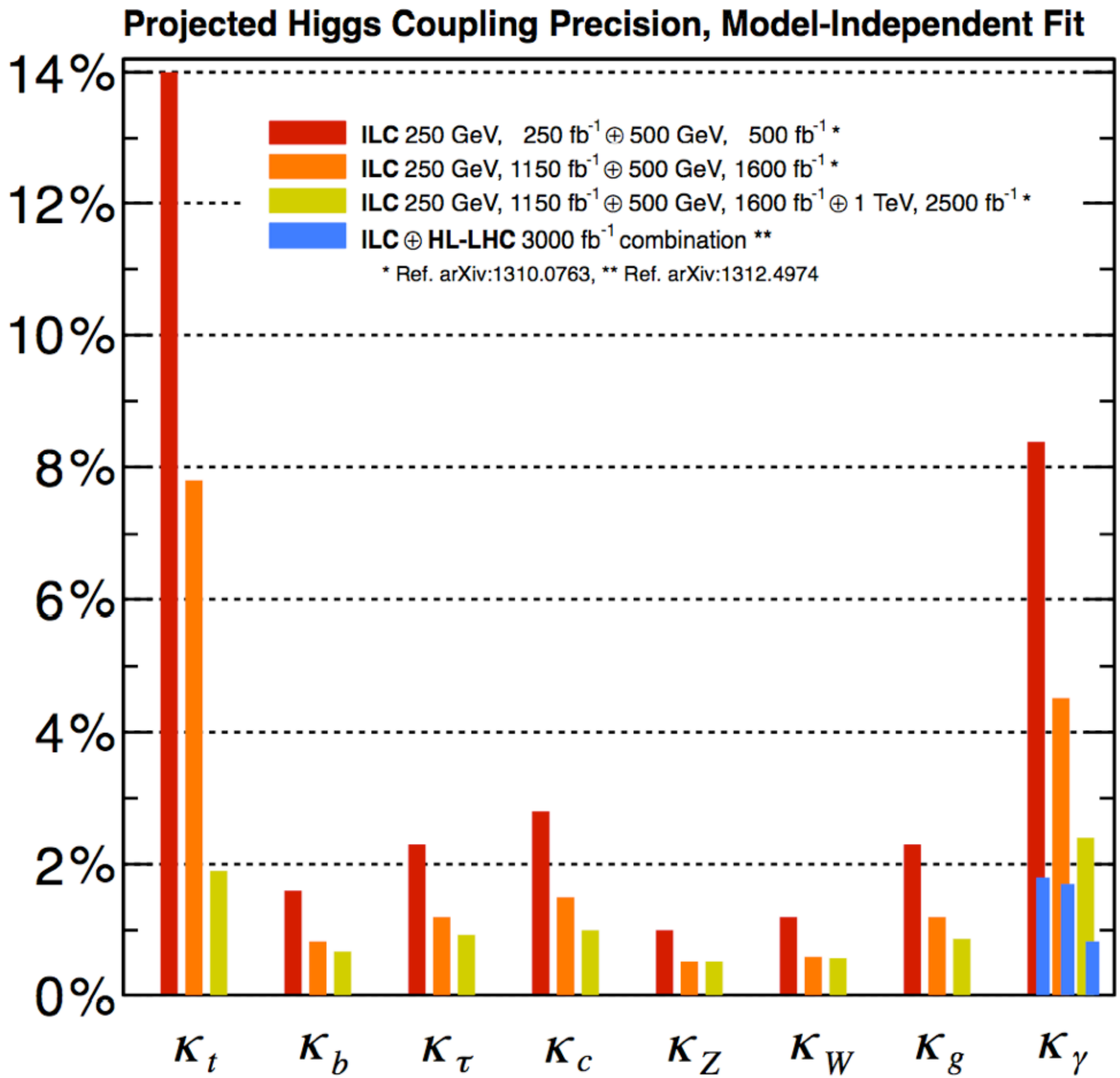
$b\bar{b}$	58%	$\tau^+\tau^-$	6.3%	$\gamma\gamma$	0.23%
WW^*	21%	$c\bar{c}$	2.9%	γZ	0.15%
gg	8.6%	ZZ^*	2.6%	$\mu^+\mu^-$	0.02%

Many decay modes of the Higgs will eventually be visible, and measurable. F. Gianotti: "Thank you, Nature."

Measurements at the International Linear Collider (ILC) in

$$e^+e^- \to Zh \qquad\qquad e^+e^- \to \nu\overline{\nu}h$$

will allow model-independent determination of the individual, absolutely normalized, partial widths for Higgs decay into these modes at the 1% level of accuracy or better.



Projected Higgs Coupling Precision, Model-Independent Fit
14%
12%
10%
8%
6%
4%
2%
0%
ILC 250 GeV, 250 fb^{-1} ⊕ 500 GeV, 500 fb^{-1} *
ILC 250 GeV, 1150 fb^{-1} ⊕ 500 GeV, 1600 fb^{-1} *
ILC 250 GeV, 1150 fb^{-1} ⊕ 500 GeV, 1600 fb^{-1} ⊕ 1 TeV, 2500 fb^{-1} *
ILC ⊕ HL-LHC 3000 fb^{-1} combination **
* Ref. arXiv:1310.0763, ** Ref. arXiv:1312.4974
κ_t
κ_b
κ_τ
κ_c
κ_Z
κ_W
κ_g
κ_γ

The study of the deviations from these predictions is guided by the idea that each Higgs coupling has its own personality and is guided by different types of new physics. This is something of a caricature, but, still, a useful one.

fermion couplings - multiple Higgs doublets

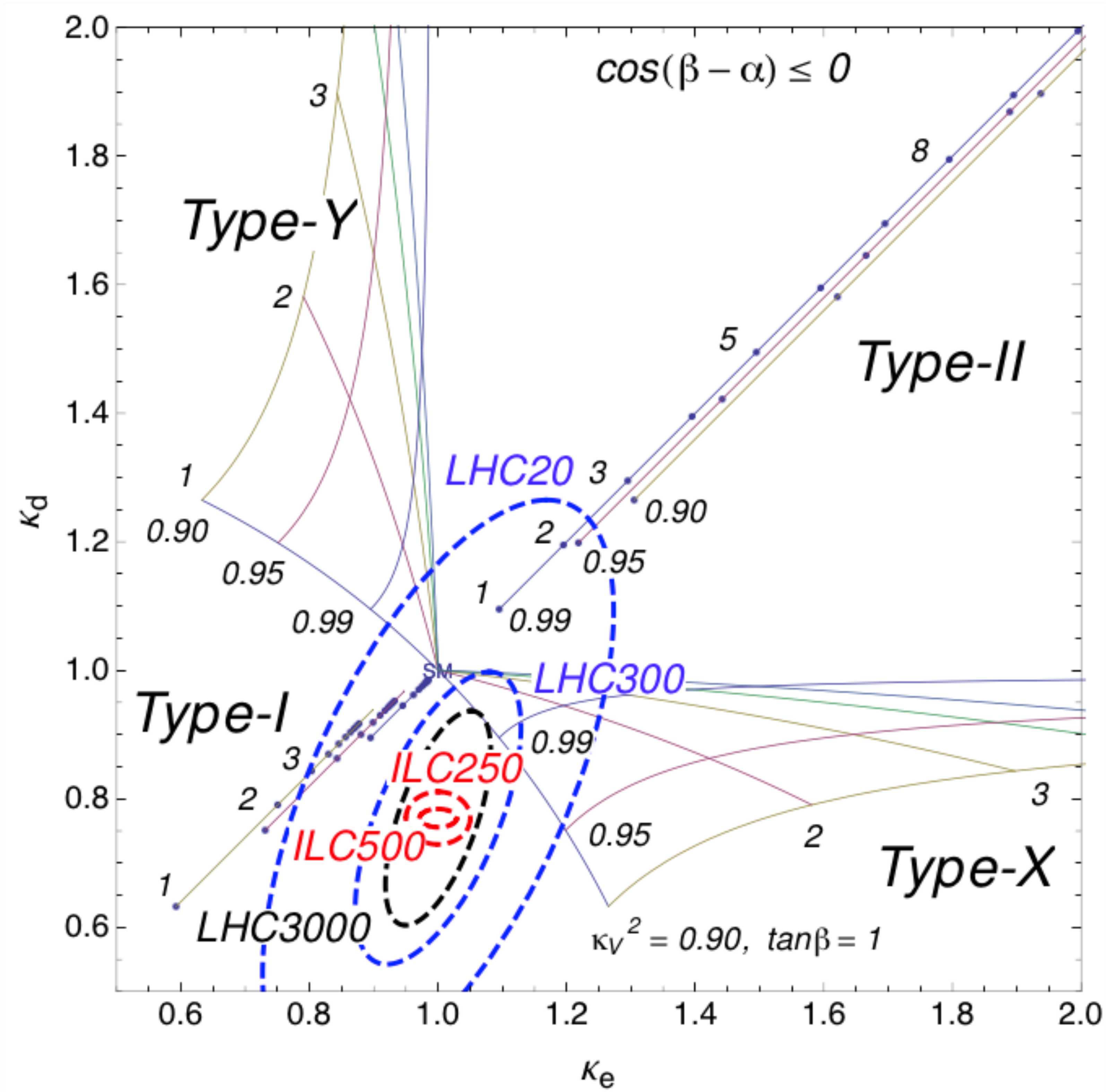
gauge boson couplings - Higgs singlets, composite Higgs

$\gamma\gamma$, gg couplings - heavy vectorlike particles

tt coupling - top compositeness

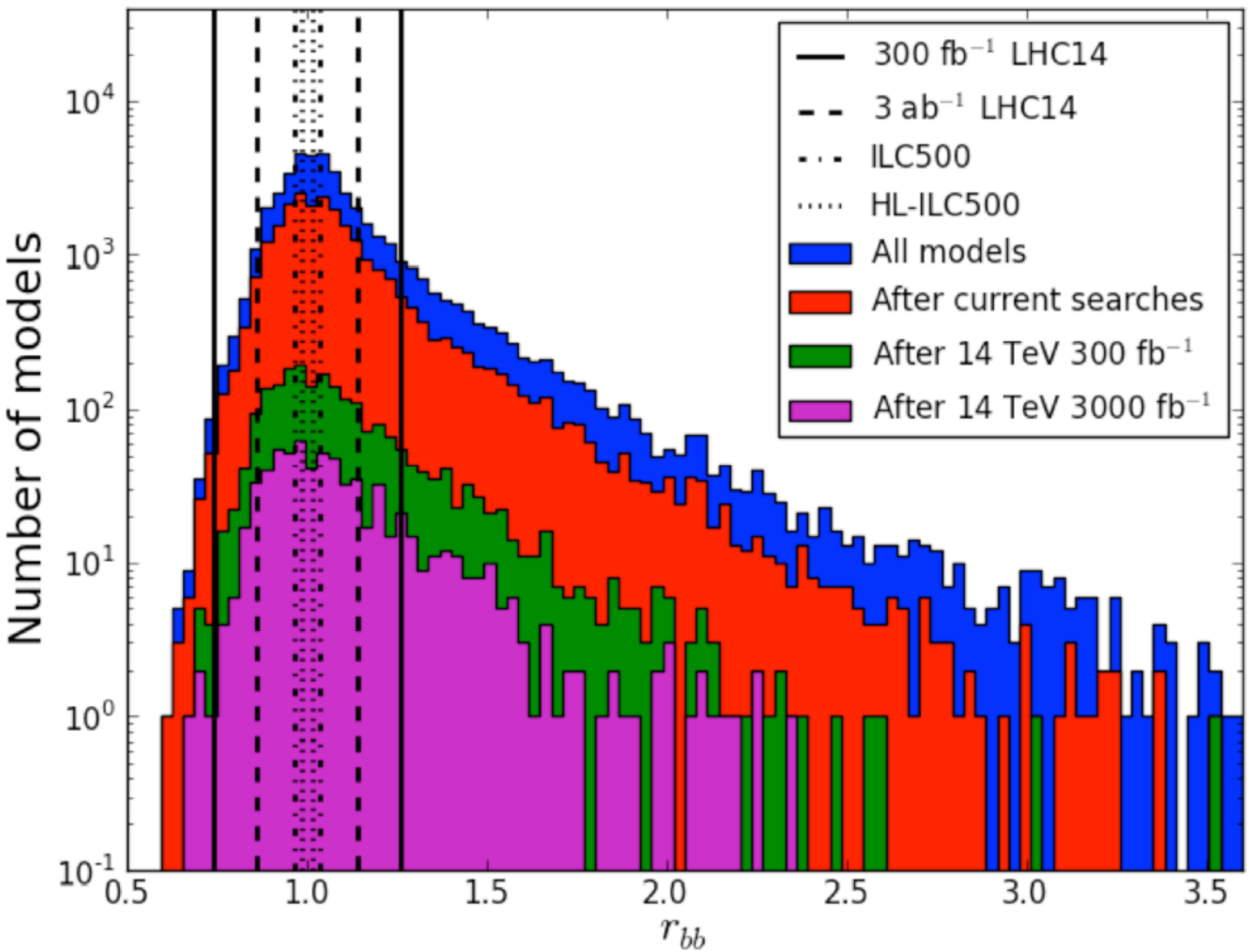
hhh coupling (large deviations) - baryogenesis

2 Higgs doublet models



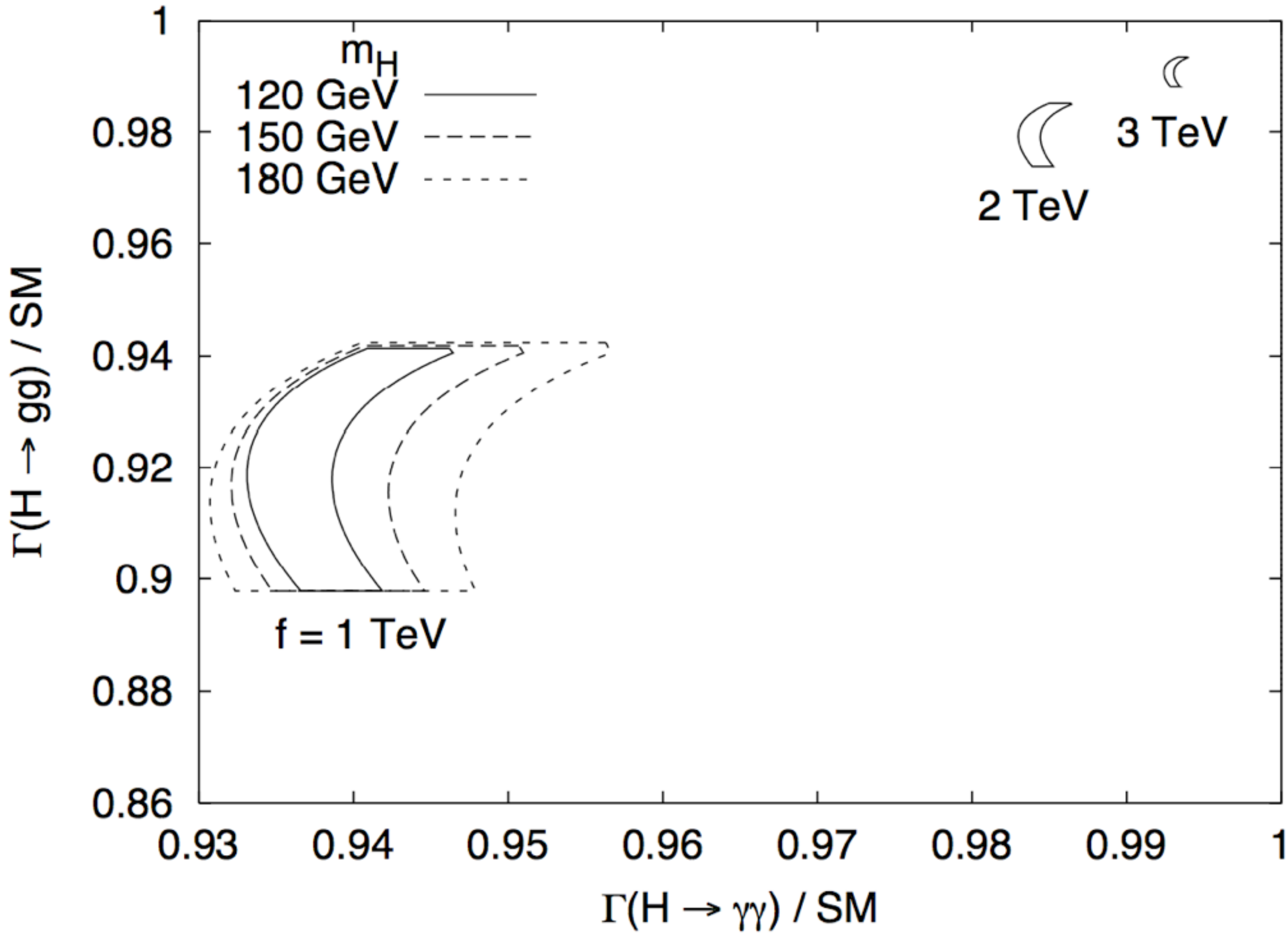
Kanemura, Tsumura, Yagyu, Yokoya

$\Gamma(h \to b\bar{b})$ in a large collection of SUSY models

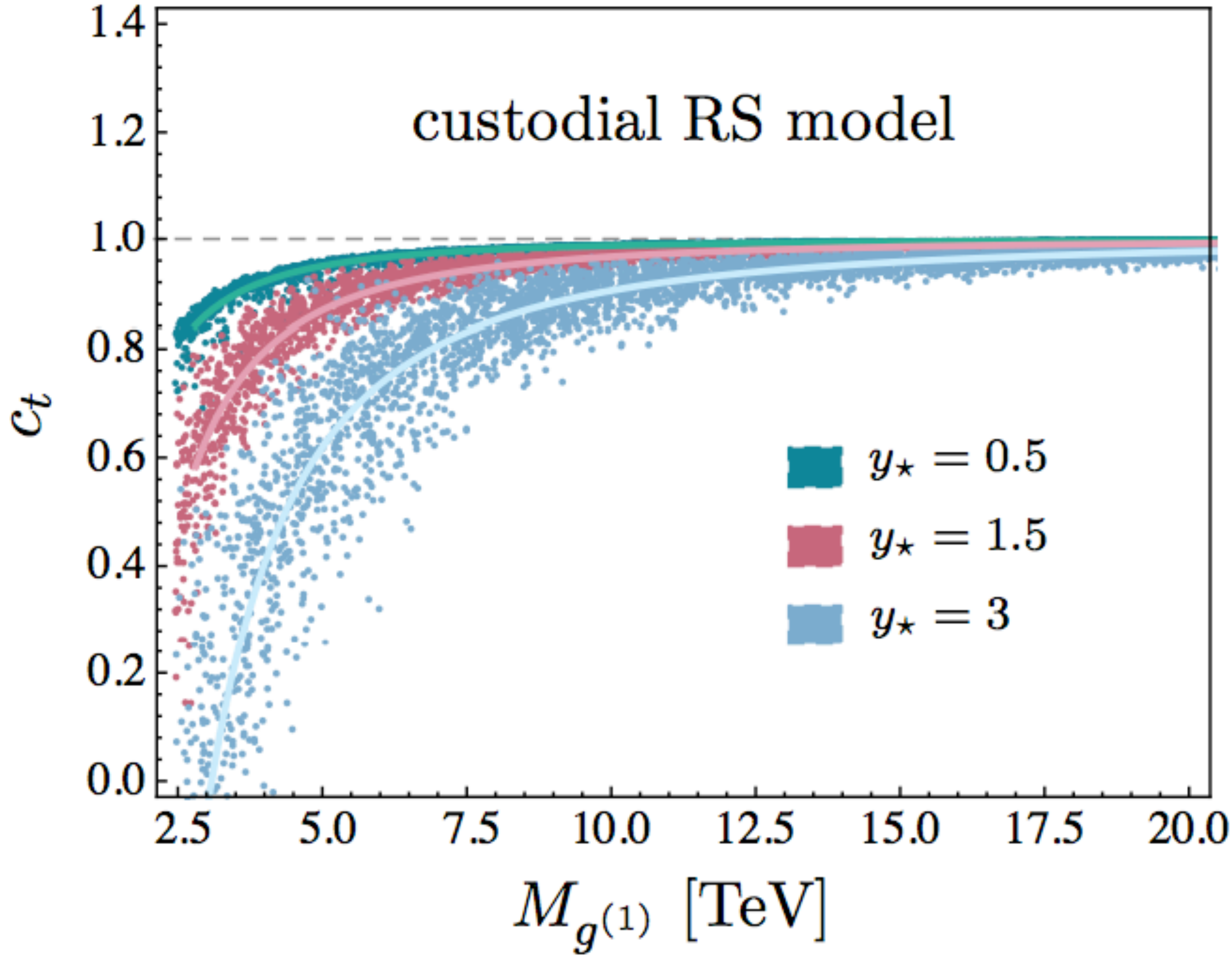


Cahill-Rowley, Hewett, Ismail, Rizzo

Littlest Higgs model



Han, Logan, McElrath, Wang

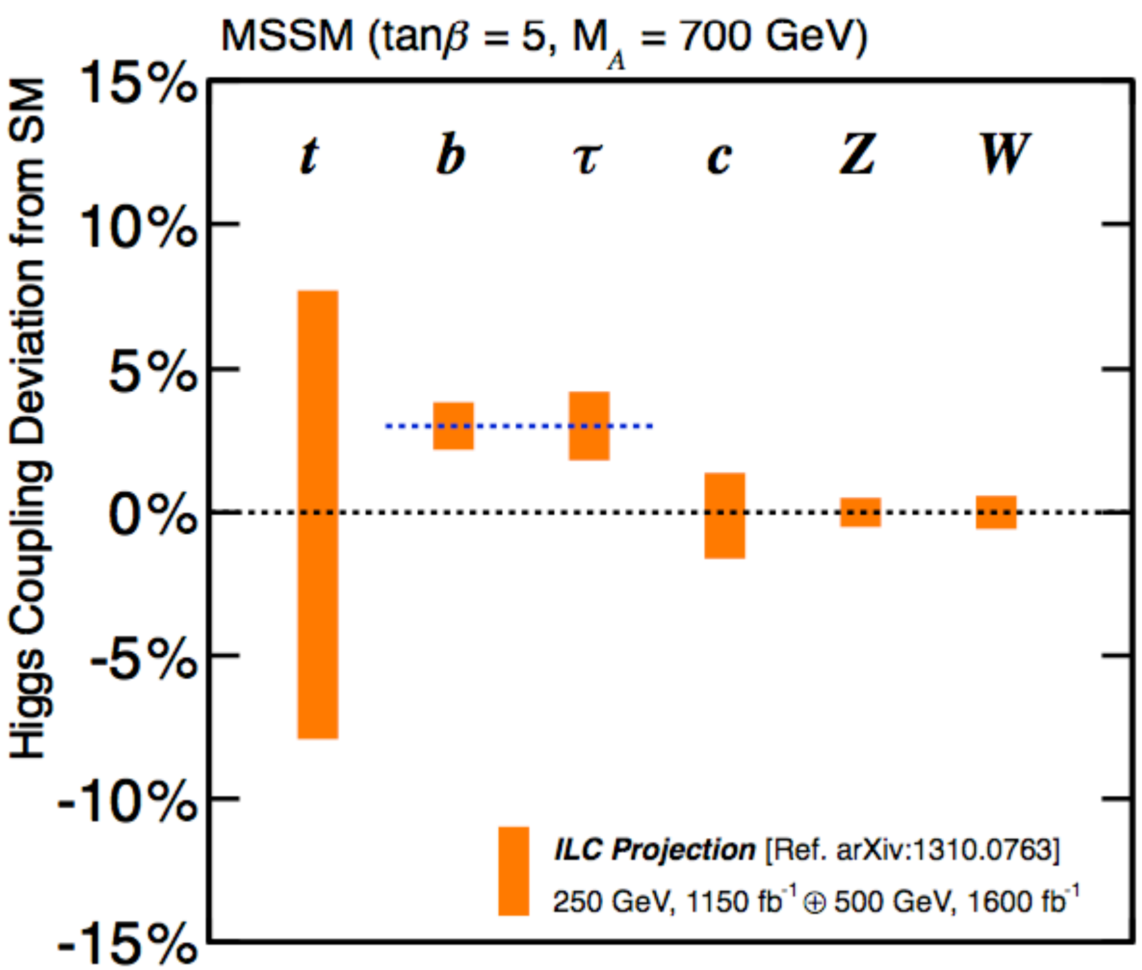


Malm, Neubert, Schmell

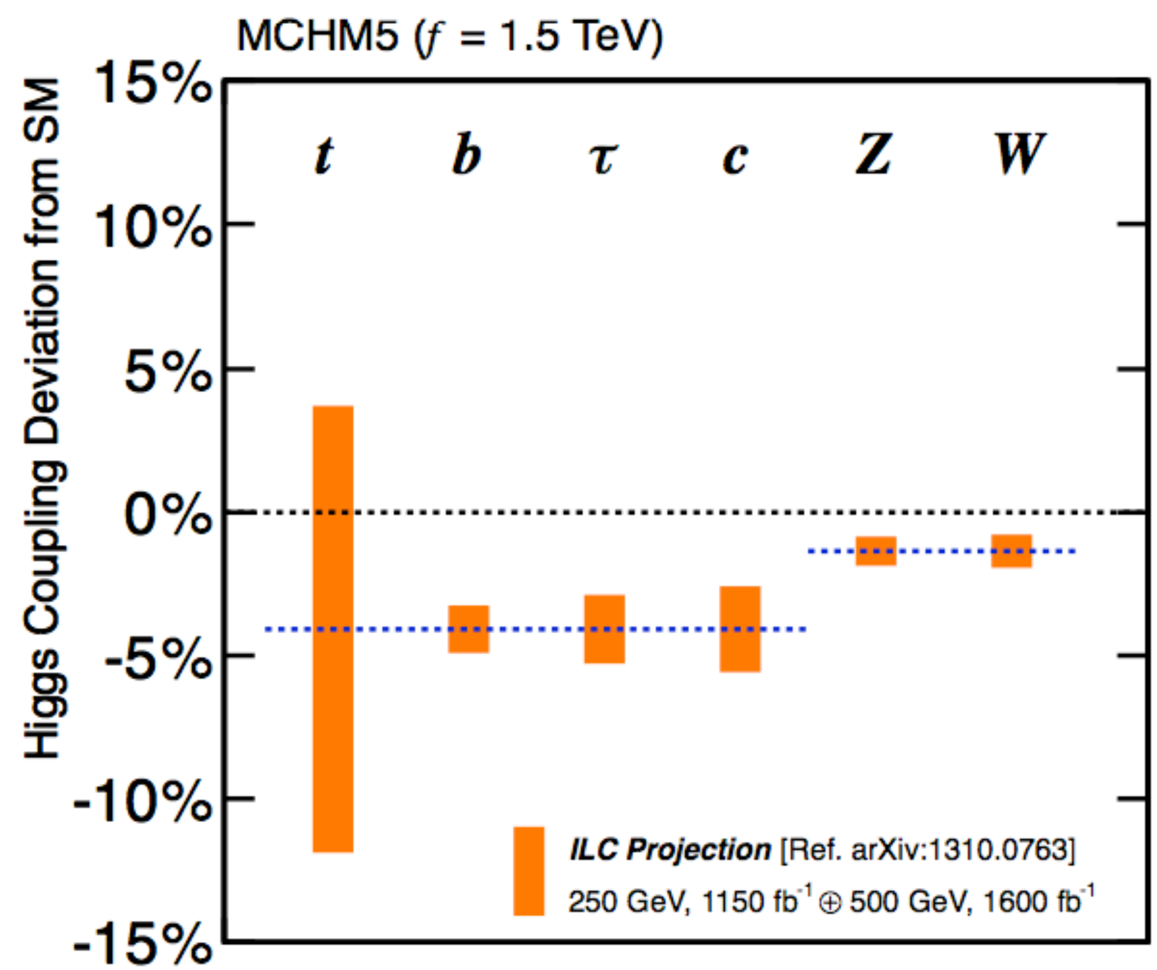
Putting all of these effects together, we find patterns of deviations from the SM predictions that are different for different schemes of new physics.

For example:

SUSY



Composite Higgs



Kanemura, Tsumura, Yagyu, Yokoya

This is a compelling program, but it requires new and very accurate Standard Model computatons.

What we will measure are the absolute values of Higgs partial widths. In order to detect a deviation from the Standard Model expectation, we must compare these to Standard Model reference values. Those values must then be computed to better than 1% accuracy.

It has been questioned in the literature whether this is possible, especially for $\Gamma(h \to b\bar{b})$, for which a very accurate value of the b quark mass is needed.

There are two types of contributions to the theoretical error on SM predictions:

error from uncalculated orders of perturbation theory

error from uncertainty in input parameters (m_b, α_s)

I will quote uncertainties in terms of quantities

$$\delta_A = \frac{1}{2} \frac{\Delta\Gamma(h \to A\overline{A})}{\Gamma(h \to A\overline{A})}$$

The partial widths to WW, ZZ also depend strongly on the mass of the Higgs boson:

$$\delta_W = 6.9 \cdot \delta m_h \ , \quad \delta_Z = 7.7 \cdot \delta m_h$$

This is a 0.2% uncertainty for $\Delta m_h = 30 \ \mathrm{MeV}$.

This is the primary motivation (in my opinion) for a very accurate Higgs mass measurement.

For the theoretical errors, the situation is quite good. These uncertainties in δ_A are currently

0.1% for Higgs couplings to quarks
2 % for Higgs couplings to gg
1 % for Higgs couplings to WW, ZZ
1 % for Higgs coupling to $\gamma\gamma$

Among the most impressive theoretical efforts are

Baikov, Chetyrkin, Kuhn: $g(hb\bar{b})$ to $\mathcal{O}(\alpha_s^4)$
Baikov, Chetyrkin,
Schreck and Steinhauser: $g(hgg)$ to $\mathcal{O}(\alpha_s^4)$
Actis, Passarino, Sturm, Uccirati: $g(hgg)$ to $\mathcal{O}(\alpha\alpha_s)$

Improvement of the current results to 0.1% accuracy is possible, though it will require dedicated effort.

Now turn to parametric uncertainties. The strongest dependences are those on m_b, m_c, α_s .

Most of the parametric dependence comes from

$$g_{hA\overline{A}} \sim m_A$$

The factors of mass must be defined carefully. The perturbation theory is free of large logarithms for

$$m_A^2 \to m_A^2(\overline{MS}, \mu = m_h)$$

This must be determined by parameter values measured at lower energies. We choose as our parameters the $\overline{MS}$ values

$$m_b(10.0 \text{ GeV}) \ , \quad m_c(3.0 \text{ GeV}) \ , \quad \alpha_s(m_Z)$$

Formulae for running $\overline{MS}$ masses are known to 4 loops.

Using RunDec (Chetyrkin-Kuhn-Steinhauser) or the private code of HPQCD, we find

$$\delta m_b(m_h) = 1.0 \cdot \delta m_b(10) \oplus (-0.38) \cdot \delta\alpha_s(m_Z)$$
$$\delta m_c(m_h) = 1.0 \cdot \delta m_c(3) \oplus (-0.90) \cdot \delta\alpha_s(m_Z) \oplus (0.006) \cdot \delta m_b(10)$$

Note that the coefficients are much larger if the quark masses are evaluated at lower scales, or at scales that depend on the quark mass. For example,

$$\delta m_b(m_h) = 1.19 \cdot \delta m_b(m_b) \oplus (-0.69) \cdot \delta\alpha_s(m_Z)$$

Combining this dependence with that from the perturbation theory, we find

$$\delta_b = 1. \cdot \delta m_b(10) \oplus (-0.28) \cdot \delta\alpha_s(m_Z)$$

$$\delta_c = 1. \cdot \delta m_c(3) \oplus (-0.80) \cdot \delta\alpha_s(m_Z)$$

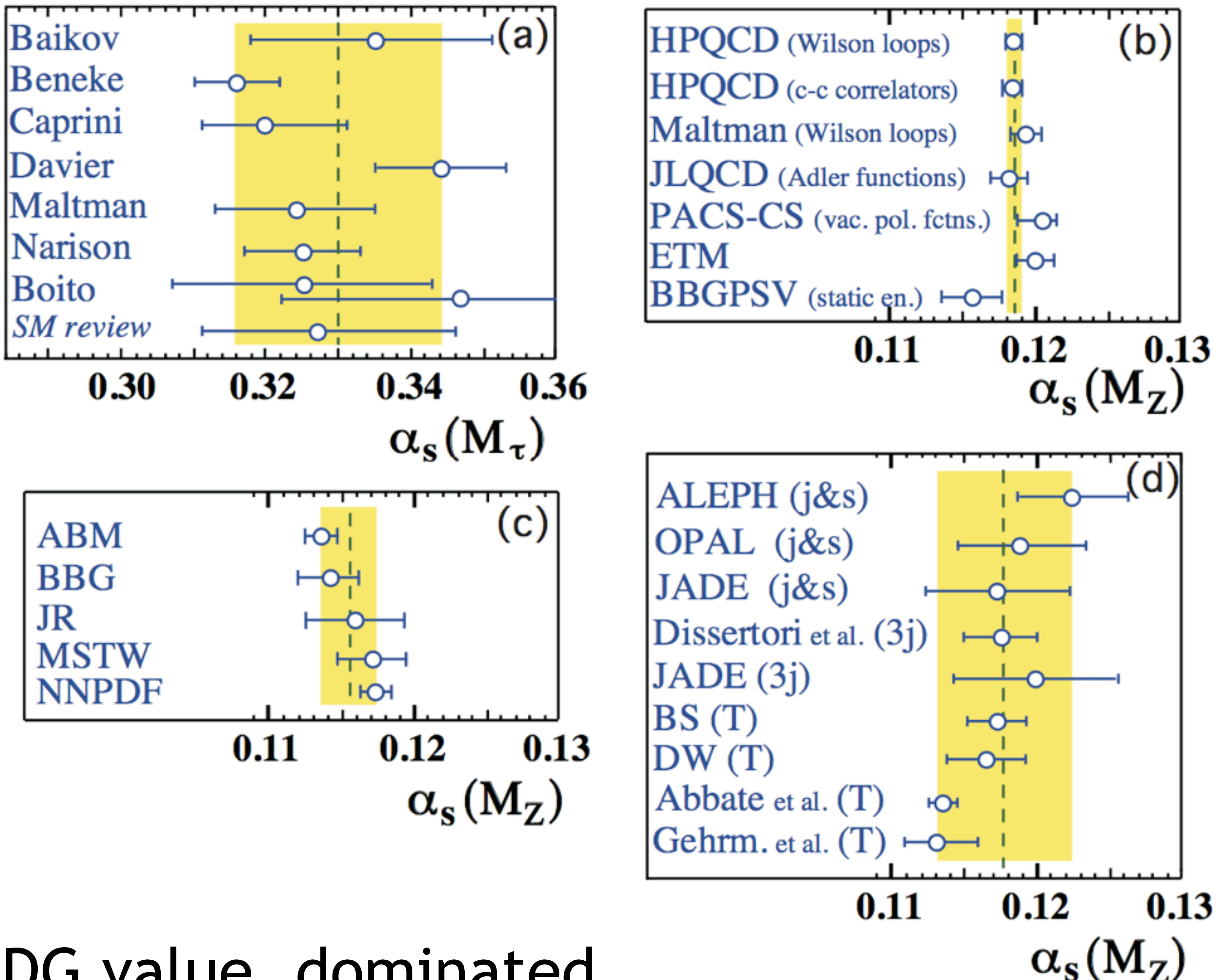
$$\delta_g = 1.2 \cdot \delta\alpha_s(m_Z)$$

The coefficients are of order 1. Thus, we still need the input parameters at the 0.1% level.

We claim that this level of precision can be achieved by lattice QCD.

Lattice QCD already gives the highest-precision measurements of α_s and measurements of precision comparable to the state of the art for heavy quark masses.

most recent PDG compilation of α_s measurements



The PDG value, dominated by lattice QCD, is $\alpha_s = 0.1185\ (6)\ (0.5\%)$

$m_b(m_b; \overline{MS})$

The current best determinations of from lattice QCD calculations of the Υ spectrum give

$$4.166\ (43)$$

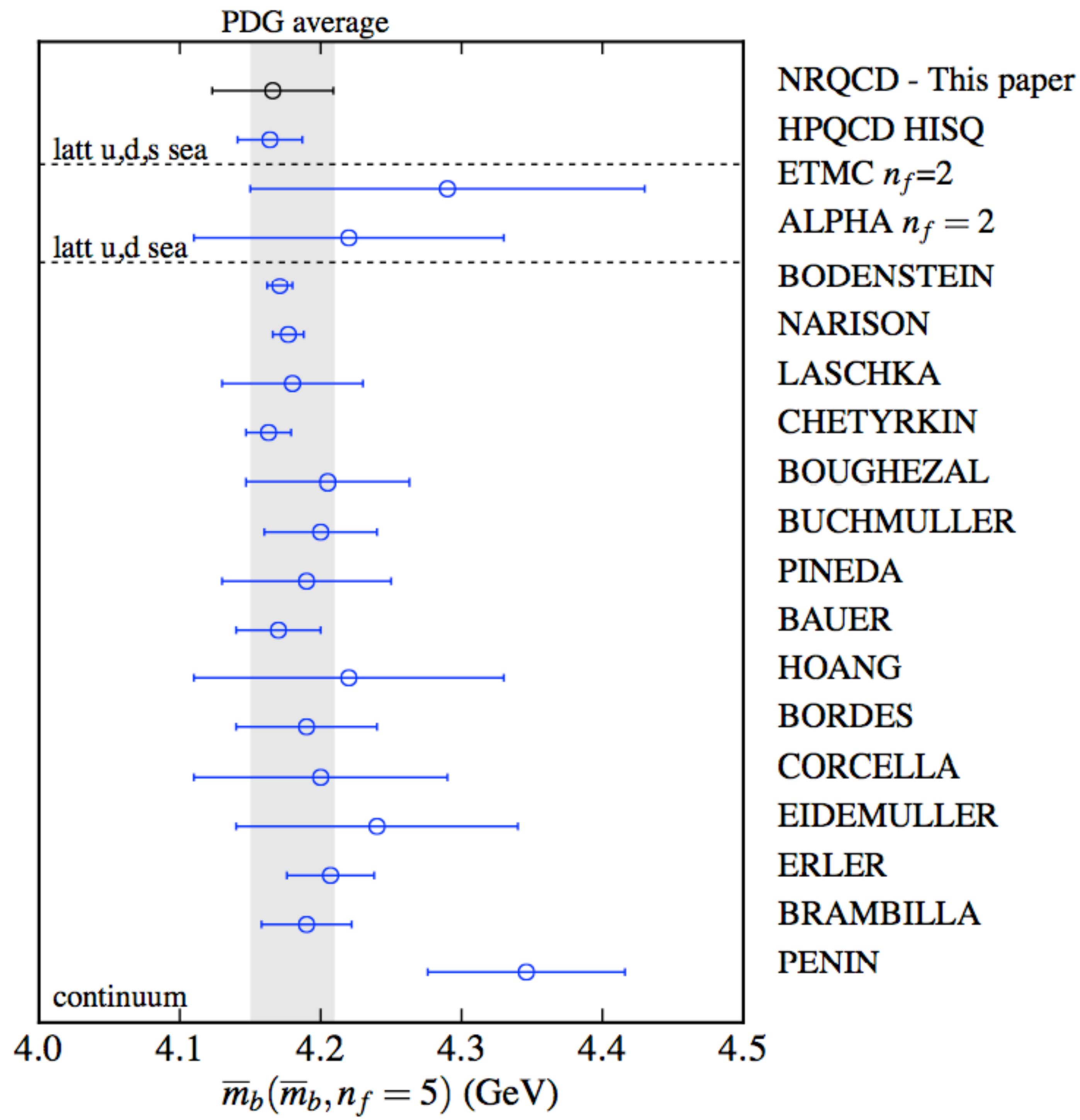
$$4.164\ (23)$$

Comparable results from QCD sum rules are

$$4.171\ (9)$$

$$4.177\ (11)$$

$$4.163\ (16)$$



From the global fit to B decay distributions using HQET (HFAG): $4.194\ (43)$

I will now describe one strategy for reaching high precision using lattice QCD (HPQCD group):

Study a 2-point correlation function

$$G(t) \equiv a^3 \sum_{\mathbf{x}} m_{0Q}^2 \langle 0 | j_{5Q}(\mathbf{x}, t)\, j_{5Q}(0,0) | 0 \rangle$$

Take moments, and extrapolate these to the continuum limit

$$G_{2n} \equiv a \sum_t t^{2n} G(t) = (-1)^n \frac{\partial^{2n}}{\partial E^{2n}} G(E=0)$$

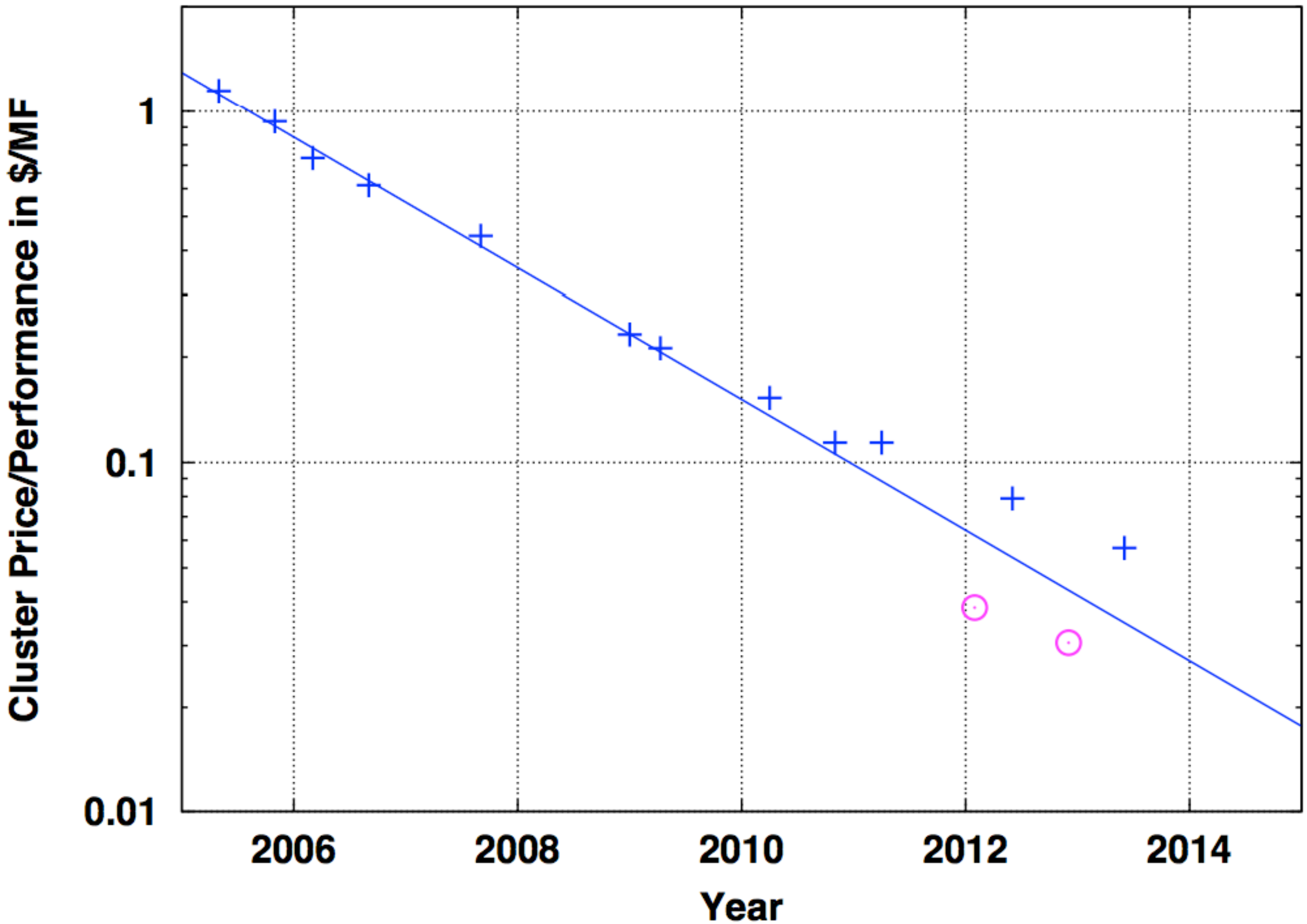
Use $f_\pi, m(\eta_c), m(\eta_b)$ to set the scale of masses for the lattice spacing. G_{2n} depends on off-shell masses at $Q \sim 2m_Q$.

This gives the continuum values of QCD sum rules. Analyze these using continuum QCD formulae with $\overline{MS}$ subtraction. This evades the need for high order QCD perturbation theory.

The perturbation expansions for the moments $2n \leq 10$ are known to 3rd order in QCD perturbation theory.

Chetyrkin-Kuhn-Sturm, Boughezal-Czakon-Schutzmaier, Maier-Maierhofer-Marquand-Smirnov

The method is similar to the direct use of experimental data, except that it is systematically improvable.



Fermilab and JLab clusters

Foreseen improvements:

LS - decrease lattice spacing from 0.045 fm to 0.03 fm

LS^2 - decrease lattice spacing from 0.045 fm to 0.023 fm

PT - compute one more order in QCD perturbation theory

ST - increase statistics by a factor 100

LS^2 requires a factor 100 increase in computing power.

fractional uncertainties in %

	$\delta m_b(10)$	$\delta \alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

Lepage-Mackenzie

Other, independent, methods are available to measure α_s in a manner uncorrelated with heavy quark masses, and to measure those masses using different techniques.

One of the most powerful ways to search for physics beyond the Standard Model will be to search for deviations in the Higgs boson couplings from their SM reference values.

The bread-and-butter program of Lattice QCD, improving the precision of our knowledge of quark masses and the QCD coupling, is essential input for this comparison.

Please devote the computing resources needed to reach the goals for precision QCD that this program requires.